Enhancing performance and reducing emissions of a spark ignition engine by adding dimethyl carbonate to gasoline

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Abstract:

Various alternative fuels have previously been investigated in light of growing concerns about environmental pollution and fuel depletion. In this study, the effects of dimethyl carbonate as an alternative oxygenate to gasoline on the performance, emissions, and combustion characteristics of an inline four-cylinder spark-ignited engine are investigated. Adding dimethyl carbonate to gasoline produced a higher Research octane number and oxygen percentage. The study found that using dimethyl carbonate/gasoline blends increased brake thermal efficiency and reduced unburned hydro carbons and carbon monoxide emissions. Furthermore, a mixture containing 30% dimethyl carbonate presented the engine's best performance and emission characteristics compared to gasoline. At higher engine speed, 8.95% higher brake thermal efficiency, 16.94% lesser HC, and 18.75% lesser CO than gasoline. A higher level of nitrogen oxide is produced by dimethyl carbonate/gasoline blends when compared to gasoline. The combustion stability and heat release rate produced by dimethyl carbonate/gasoline blends were higher than gasoline.

Keywords: Oxygenates; Gasoline; Oxygen enrichment; Emission reduction; Octane number

<u>Abbreviations</u>

HC	- Hydrocarbon
CO	- Carbon monoxide
UG	- 100% unleaded gasoline
DMC	- Di Methyl Carbonate

MPFI	- Multi-point fuel injection
DMC 10	- 10% Dimethyl Carbonate + 90% gasoline
DMC 20	- 20% Dimethyl Carbonate + 80% gasoline
DMC 30	- 30% Dimethyl Carbonate + 70% gasoline
CO_2	- Carbon dioxide
NOx	- Nitrogen oxide
RON	- Research octane number
ROHR	- Rate of heat release
AKI	- Anti knock index
γ	- volume fraction of DMC
ρ_f	- Density of blended fuel
ρ_D	- Density of DMC
ρ_g	- Density of gasoline
h_f	- Calorific value
h_D	- Calorific value of DMC
h_g	- Calorific value of gasoline
ϕ_f	- Air-fuel ratio (fuel blend)
ϕ_D	- Air-fuel ratio of DMC
ϕ_g	- Air-fuel ratio of gasoline
ON_f	- Octane number of blended fuel
ON_D	- Octane number of DMC
ON_g	- Octane number of gasoline

1. Introduction

In recent years, there has been great concern about atmospheric pollution. Mainstream greenhouse gas emissions from industries, logistics, and transport activities encompass more than 600 million combusting units, which is estimated to increase by the year 2050 [1]. There are also concerns regarding the depletion of fossil fuels such as gasoline, diesel, etc. Alternatives for gasoline and diesel have been rigorously researched for the past 5 to 6 decades. Moreover, gasoline is known to emit higher organic emissions. To address the issues mentioned above, researchers investigated a new fuel that can either be blended with gasoline or used directly in spark-ignited (SI) engines [2]. Ethanol is one such fuel that has been used in some places as an alternative to gasoline. Various other fuels, such as methanol, butanol, propanol, acetone, 2,5-dimethyl furan (DMF), diisopropyl ether, methyl-tert butyl ether (MTBE) etc., were proposed as an alternative for gasoline [3, 4]. A common thing in almost all the fuels proposed as alternatives for gasoline is the presence of oxygen. It has been established that the presence of oxygen lowers emissions of hydrocarbons (HC) and carbon monoxide (CO). The use of oxygenates in SI engines, rather than gasoline, is attributed to high octane ratings, a high latent heat of vaporization, and other favorable characteristics [5].

Iodice P et al. [6] reviewed and found that NOx emissions exhibit a decreasing trend with an increase in ethanol concentration within ethanol/gasoline blends. This phenomenon can be attributed to the elevated latent heat of vaporization and lower heating value of gasoline/ethanol mixtures compared to conventional gasoline. Additionally, as the air/fuel mixture drops after the intake stroke, a subsequent reduction in combustion temperature occurs, leading to diminished thermal NO_X emissions. Topgul [7] tested 5, 10, 20, and 30% blended MTBE/gasoline blends in a single-cylinder SI engine for a speed range of 1500–5000 rpm at full load. He observed that using 10% blended fuel at 2500 rpm produced the highest brake thermal efficiency among all blends tested. Using MTBE/gasoline blends reduced CO and HC emissions by 27.3% and 87.3%, respectively. Li et al. [8] studied the effect of using an ethanol/gasoline blend on exhaust and evaporative emissions. They found an increase in NOx emissions and a reduction in HC, CO, and volatile organic compounds by substituting ethanol in gasoline by 10%. In a single-cylinder engine, Wei et al. [9] evaluated 10% blends of 2,5-dimethylfuran/gasoline and ethanol/gasoline. They observed that, although the use of a 2,5-dimethylfuran blend resulted in higher emissions of CO, HC, and NOx compared to an ethanol blend, it enhanced combustion stability.

A review conducted by Dehhaghi et al. [10] on the impact of nano additives on gasoline engine performance and emission characteristics revealed that these additives play a vital role in enhancing various aspects. The heat-transfer rate during gasoline combustion is notably increased, facilitated by nano additives which, akin to metallic nanoparticles, induce micro-explosions, thereby accelerating combustion. The introduction of these nano additives results in decreased gasoline viscosity, facilitating fuel slipping. Furthermore, improvements in the gasoline octane number and a reduction in smoke formation are noted. Gravalos et al. [11] the fuel blend performances of methanol, ethanol, propanol, butanol, and pentanol were compared with gasoline in a single-cylinder carbureted engine. It has been discovered that 40% of alcohol blends emit less CO than gasoline. Lower HC emissions are produced when the oxygenate concentration in gasoline is increased. Among the blends, pentanol and butanol produced lower HC emissions. Except for the 40% alcohol blends, the NOx levels emitted were quite similar. Gopinath D and Ganapathy Sundaram E [12] experimented with DMC as an oxygenated mixture with gasoline in a multi-cylinder carburetor engine. DMC-gasoline blends of 5%, 10%, 15%, and 20% were used to power the engine. Increasing DMC content in gasoline resulted in higher BTE, lower HC and CO emissions. DMC20 blend increases BTE by 2.5% compared to gasoline, and in terms of emissions, HC and CO result in lower levels of 200 ppm and 0.25%, respectively, compared to gasoline.

In an experimental study by Schifter et al. [13], ethanol, ethyl-tert-butyl ether, and dimethyl carbonate blends were tested and compared with gasoline in a single-cylinder spark ignition engine. DMC and EtOH increase the combustion speed relative to gasoline due to their good oxygenate characteristics, resulting in an increase in IMEP. Li Xiaolu et al. [14] investigated the combustion and emission characteristics of DMC as a blended fuel in a diesel engine. DMC's high latent heat of evaporation resulted in lower thermal efficiency at low load conditions. Due to low thermal efficiency, the engine could not produce more heat, resulting in higher HC emissions. The higher latent heat of evaporation of DMC produced a lower heat release rate compared to diesel. Cheung et al. [15], conducted an emission test in a CI engine, blending DMC (0%, 5%, 10%, 15%, 20%, and 30%) with diesel. Oxygen content DMC provides oxygen during diffusion combustion, resulting in reduced particulate and smoke opacity. DMC at 5% in diesel produced good results in reducing PM and smoke levels compared to others. On the other hand, DMC-blend diesel produced higher HC and CO, and there is no change in NOx emissions. Deqing Mei et al. [16] conducted experiment to investigate the combustion and emission characteristics of DMC blended with diesel in a single-cylinder CI, PCCI CRDI engine. The low boiling point of DMC produces the heat earlier, which strengthens the constant volume degree of the thermodynamic cycle; higher results indicate higher thermal efficiency for D10. Instantaneous heat release rate is higher than diesel for D10 during the initial period, so the evaporation of DMC improves with the mixing of fuel and air, which produces a higher in-cylinder pressure and heat release rate. Higher oxygen percentages in DMC reduced CO, HC, and PM emissions for D10.

Saravanakumar et al. [17] investigated the effects of DMC as an additive in Calophyllum inophyllum methyl ester (CIME)-diesel blends at various compression ratios on performance and emissions. The oxygen in biodiesel and additives causes fuel premixed phase combustion, which improves thermal efficiency and combustion. B20 with DMC produces 27.8% higher BTE compared to other blends and diesel. CO is reduced by 47% and HC emissions are reduced by 35.5%; this is due to the leaning effect of DMC present in the fuel; on the other hand, NOx is increased. Rounce et al. [18], showed that DMC-blend diesel produced more NOx and less THC, CO, and PM when compared to diesel. Oxygenate (DMC) produced increased cylinder pressures (with higher temperatures) and, as well, increased periods of time during higher pressures, resulting in higher NOx. Fuel-born oxygen compounds in DMC reduced HC, CO, and PM up to 50% for 4% DMC in diesel. Huang et al. [19] demonstrated that mixing DMC with diesel results in longer premixed combustion and shorter diffusive combustion. Higher cylinder pressure and a higher heat release rate are produced due to the addition of DMC. The same research group studied the emission characteristics of DMC in a DI diesel engine. The addition of 10% DMC to diesel has resulted in a reduction in smoke levels at the same time that NOx has increased. Lan-bin Wen et al. [20], experimented with the effects of adding ethanol and DMC to gasoline on the performance and emissions of a single cylinder SI engine. Due to a shorter combustion time at a higher engine speed, less CO emissions were observed. HC emissions were reduced by about 35% compared to gasoline. This is due to the combustion duration and oxygen content in DMC and ethanol. NOx concentrations decreased at some speeds, most likely due to a lower heating value resulting in a lower flame temperature.

This study explores the effects of adding DMC ($C_3H_6O_3$) as an oxygenate to gasoline on the emission performance and combustion characteristics of a multi-cylinder MPFI engine, contributing to the limited experimental studies available in the literature. The unique properties of DMC, as a member of the ester family, make it a promising oxygenate additive, and its higher-octane number opens up opportunities for improved engine performance, particularly through higher compression ratios.

2. Experimental setup and procedure

2.1. Engine test setup

The tests were performed on a Maruti Zen's inline four-cylinder, four-stroke MPFI SI engine manufactured by Suzuki. The engine was loaded by an eddy current dynamometer (TMEC50, TECHNOMECH, Pune, India) connected to the engine shaft for loading. Fuel flow was monitored using an electronic balance to the strain gauge. At the same time, intake air was measured using a mass airflow sensor integrated into the air tank. A water-cooled, stand-alone piezoelectric pressure transducer mounted on the first cylinder head to measure in cylinder pressure. Additionally, the angle was measured using an encoder. A standard air tank with orifice plates is fixed to the rig to measure the actual volume of air drawn into the cylinder. Using signal conditioning, the parameters are routed to the computer. At various points in the system, the thermocouples necessary for the measurement of temperature are provided and are being routed to the computer. Using a non-contact proximity sensor, the engine is measured. Parameters relating to speed and torque are routed to the computer. The test engine specifications are given in Tables 1. The experimental setup is depicted in Figure 1, and a photograph of the experimental setup is shown in Figure 2.

2.2.Emission measurement

HC and CO exhaust gases were measured using non-dispersive infrared sensors through a multi-gas analyzer (NPM-MGA-1, Netel India Limited, Mumbai, India). NOx gas measurements were also conducted with the same instrument, utilizing an electrochemical sensor.

2.3.Test Procedure

The test engine was operated in the range of 1400 rpm to 2800 rpm, with 200 rpm increments, and a consistent load of 25 Nm was maintained throughout. The engine was allowed to run for as long as necessary to consume the remaining fuel from the previous experiment. Once the engine reached a stable condition, measurements were taken at regular intervals, and data were recorded for each measurement. A K-type thermocouple was used for measuring the temperatures. The tests were repeated three times, and average values were taken. A standard gas analyzer leak test was performed before measurement. When steady-state conditions were displayed on the gas analyzer's LCD screen, the probe of the gas analyzer was then inserted into the extension pipe. The in-cylinder pressure was measured at each crank angle using a piezoelectric transducer.

After conducting all tests, values were retrieved from the software provided by the engine supplier, and graphs were plotted to compare blends of dimethyl carbonate (DMC10, DMC20, and DMC30) against UG.

2.4. Test fuel

DMC is the simplest organic compound, which has an important role in the chemical industry due to its flexibility and wide range of applications. Dimethyl carbonate is one of the green chemicals for sustainable processes due to its low toxicity to humans and other life forms. Dimethyl carbonate is a colourless liquid with a higher auto-ignition temperature and octane number than gasoline, which eliminates (or reduces) knocking in SI engines. Dimethyl carbonate can be produced by the oxidative carbonylation route, the alkylene carbonate route, inorganic routes, urea alcoholysis, and phosgene alcoholysis. Dimethyl carbonate used for the purpose of oxygenation is commonly produced via the oxidative carbonylation route [21,22]. The production synthesis and molecular structure of DMC are shown in Figure 3 and Figure 4. The properties of dimethyl carbonate and gasoline are shown in Table 2. DMC's low miscibility in water (about 13.9 g/100 ml, makes it better than ethanol. Unleaded gasoline (UG) was obtained from a local gasoline station, and dimethyl carbonate (DMC) was obtained from a local chemical supplier (Lab Chemicals, Chennai, India). Blends comprising 10%, 20%, and 30% by volume of DMC in UG were prepared (DMC 10, DMC 20, and DMC 30).

The following procedure calculates the specifications of the DMC-gasoline blends. Density, calorific value, stoichiometric air-fuel ratio, and octane number values of fuel blends are calculated using equations 1, 2, 3, and 4, respectively. The gasoline/DMC blended properties are shown in Table 3.

$$\rho_f = \gamma(\rho_D - \rho_g) + \rho_g \tag{1}$$

$$h_f = \frac{\gamma((h_D\rho_D - h_g\rho_g) + h_D\rho_D}{\rho_f} \tag{2}$$

$$\phi_f = \frac{\gamma((\phi_D\rho_D - \phi_g\rho_g) + \phi_D\rho_D)}{\rho_f} \tag{3}$$

$$ON_f = x * ON_g + y * ON_D \tag{4}$$

2.5. Error analysis of experimental data

It is essential to evaluate the uncertainty of the experiment. The uncertainty in experimental observations arises from various sources, including errors in reading, environmental conditions, instrument selection, instrument calibration, working conditions, etc. The uncertainty associated with each instrument was calculated based on its accuracy [23]. The uncertainty percentage for this experiment was calculated using the formula,

$$\left[\sum_{i=1}^{n}(U_{xi})^2\right]^{1/2}$$

where U_{xi} is the uncertainty associated with each of the measured value using corresponding instrument. Details of the parameters measured, instrument range, instrument accuracy, and the percentage uncertainty associated are listed in Table 4. The calculated uncertainties for performance measurement, properties measuring instruments, and emission instruments are ± 0.654%, ± 0.378%, and ± 0.463%, respectively. For the entire experiment, the calculated uncertainty is ± 1.495%.

3. Results and discussion

3.1. Performance characteristics

Brake Thermal Efficiency (BTE) serves as an indicator of an engine's ability to convert the chemical energy of fuel into useful work. Figure 5 illustrates the variation of BTE with speed at a load of 25 Nm. It is observed that, at any particular speed, increasing the DMC concentration in the blend results in an increase in BTE, surpassing that of gasoline. It is also observed that BTE increases with an increase in engine speed, this is because higher speeds will assist in the proper mixing of air and fuel inside the combustion chamber due to turbulence and thereby release more heat energy. Because DMC has a higher latent heat of vaporisation (369 KJ/Kg) than gasoline (305 KJ/Kg), it will absorb more heat to convert the liquid to vapour. This heat is absorbed from the cylinder walls during the compression stroke, thereby reducing the heat loss through the cylinder walls and increasing the brake thermal efficiency. In addition to the high latent heat of vaporisation of DMC, its inherently high oxygen content improved the combustion process, i.e., leading to a complete combustion process and eventually leading to improved brake thermal efficiencies [24, 25]. DMC-gasoline blends have a higher-octane index (OI) and a higher charge cooling effect; this anti knock excellence is related to compactness, and the reduced HC emissions in the combustion process produced increased BTE. At 2800 rpm, DMC10, DMC20, and DMC30, exhibited 3.86, 5.49, and 8.95% higher efficiencies than UG.

Engine stability is an important factor indicating engine performance and can be evaluated by cyclic variation. Figure 6 shows the coefficient of variation in indicated mean effective pressure (COV_{IMEP}) versus rotational speed. COV_{IMEP} are calculated using equation (5), which is the standard deviation of the indicated mean effective pressure divided by the mean indicated mean effective pressure and expressed in percentage as:

$$COV_{IMEP} = \frac{\sigma_{IMEP}}{IMEP} * 100 \qquad (5)$$

From Figure 6, it can be seen that the COV_{IMEP} of DMC/gasoline blends is consistently lower than gasoline. DMC supports gasoline burning, improves the rapidity of blended fuel combustion, stabilises engine operation, and reduces COV_{IMEP}. The higher laminar flame speed and oxygen content property of DMC are helpful in improving the homogeneity of the air-fuel mixture and lead to decreased cyclic variability of IMEP, which consequently helps reduce COV_{IMEP} [26, 27].

3.2. Emission characteristics

Hydrocarbon (HC) emissions in engine exhaust indicate incomplete combustion of hydrocarbon fuel. Various sources that contribute to the formation of HC emissions are mixtures in crevices (about 38%), oil deposits and oil layers (16%), flame quenching (about 5%), liquid fuel effects inside the cylinder (20%), and leakage in the exhaust valve (about a little less than 7%). Therefore, it can be concluded that HC emissions formation in an engine depends upon engine configuration, residence time, oxygen availability, and the structure of the fuel [28].

Figure 7 shows the variation of HC emissions of various fuel blends tested at speeds ranging from 1400 rpm to 2800 rpm and at a constant load of 25 Nm. It can be seen that DMC or gasoline produced lower HC emissions than diesel at all engine speeds. Because of the high oxygen content of DMC, the HC emission trend decreases as the DMC content of DMC/gasoline blends increases (see Table 3). HC also decreases with an increase in engine speed. This is because when the speed is increased, more fuel will be injected into the cylinder, and more fuel means more oxygen because of the inherent oxygen already present in the DMC. This oxygen present in DMC promotes complete combustion and helps in the complete oxidation of the carbon content of the fuel to CO_2 and water. At the same time, the high volatility of DMC improves the evaporation of the DMC/gasoline blend inside the cylinder, forms a homogeneous mixture, and ensures complete combustion, thereby reducing HC emissions. DMC10, DMC20, and DMC30 emitted less than UG at 1400 rpm, emitting 5.35, 12.5, and 15.17% of HC, respectively. At 2800 rpm, DMC10, DMC20, and DMC30 emitted 6.78, 15.24, and 16.94% less HC emissions than gasoline, respectively. An increase in engine speed will create turbulence in the combustion chamber and mix air and fuel properly. Oxidation of the maximum amount of HC in the fuel into H_2O and CO_2 is done by proper mixing of air and fuel [29].

Carbon monoxide is a highly toxic, colourless, odorless, and tasteless gas. Complete combustion of fuel in the presence of sufficient oxygen will produce carbon dioxide and water as products. The formation of CO also means a loss in chemical energy [30]. Fuel carbon content, flame propagation velocity, and in-cylinder residence are causes that lead to the formation of CO in the SI engine process [31]. From Figure 8, when comparing with DMC/gasoline blends, it is observed that gasoline emits higher CO emissions. CO emissions also decreased with increased DMC content in DMC/gasoline blends. Lower speeds reduced CO emissions more than higher speeds because the fuel had more combustion time to be converted to CO_2 [32]. One main reason for the lower CO emissions of DMC/gasoline blends than gasoline is because the DMC molecular oxygen is used to oxidise the hydrocarbon part of the blends and, as well, it favours the oxidising reaction of the CO to CO_2.

When DMC is mixed, the carbon mole fraction in fuel blends is reduced, which reduces CO in the flame propagation process. The flame propagation velocity is higher for DMC than gasoline; thus, DMC/gasoline blends reduce the combustion duration, resulting in less CO emission [33]. Higher flame propagation velocities result in longer in-cylinder residence time because CO in the combustion chamber takes longer to oxidise in the high temperature environment. Among other blends, DMC 30 blend emitted the lowest CO emissions, which can be attributed to the high oxygen content present in the blend, causing a leaning effect. At 2800 rpm, DMC10, DMC20, and DMC30 emitted 6.25, 12.50, and 18.75% fewer CO emissions than gasoline.

NOx formation generally follows Zeldovich mechanism consisting of following series of equations:

$$O + N_2 = NO + N \quad (6)$$

$$N + O_2 = NO + O \quad (7)$$

$$N + OH = NO + H \quad (8)$$

According to Zeldovich's mechanism, nitrogen oxidation in the post-flame oxidation zone produces thermal NOx. Typically, NOx formation occurs at high temperatures exceeding 1800 K, as breaking the triple bond in nitrogen becomes challenging. The dissociation of the O_2 molecule at higher temperatures generates free oxygen atoms, initiating a simple chain mechanism as postulated by Zeldovich [34].

Figure 9 compares the variation of NOx emissions with engine speed for DMC/gasoline blends. According to the Zeldovich mechanism, NOx formation mainly depends on combustion temperature, oxygen content, residence time, and in-cylinder temperature. DMC/gasoline blends emitted higher NOx emissions than gasoline for all engine speeds and with an increase in DMC content in gasoline. At lower speeds, the amount of fuel required is less, whereas at higher speeds, it requires more fuel to ignite. DMC/gasoline contains more oxygen than gasoline; fuel ignition at higher engine speeds means more oxygen burning in the charge. This oxygen burning results in a higher in-cylinder temperature, which explains why the NOx emission increases with increased speed. The lower boiling point of DMC (91^{o}C) promotes light and medium hydrocarbons in the DMC-gasoline blends, this low boiling temperature makes heavy hydrocarbons evaporate and form combustible mixtures. At the same time, more DMC-gasoline is injected due to its low energy density compared to gasoline, so more fuel impingement would be expected. These reasons could have caused diffuse combustion in the combustion chamber. NOx emissions are higher when diffuse combustion is observed [35]. At 2800 rpm, DMC/gasoline blends DMC 10, DMC 20, and DMC 30 emitted 3.12, 7.48, and 11.32% higher noxious emissions than UG.

3.3. Combustion characteristics

The combustion efficiency of an engine is an indicator of the degree of complete combustion of fuel inside the combustion chamber. The pressure inside the combustion chamber varies throughout the engine cycle. The variation of in-cylinder pressure and heat release rate at different crank angles gives an idea about the combustion quality inside the cylinder. Figure 10 depicts the variation of in-cylinder pressure with crank angle at 2800 rpm and 25 Nm load condition. Complete combustion due to the high oxygen content of DMC has resulted in high in-cylinder pressures and a high rate of heat release for DMC/gasoline blends. The high-octane number of DMC has resulted in high knock suppression and advanced combustion phasing, resulting in improved combustion efficiency over gasoline [36, 37]. DMC30 had the highest peak pressure at 9^{o}ATDC, DMC20 at 10^{o}ATDC, and DMC10 at 11^{o}ATDC for DMC/gasoline blends. Peak in-cylinder pressure for gasoline also occurred at 11^{o} ATDC. The in-cylinder pressure values also increased as the blend percentage increased. The peak pressure values of 30.7, 31.1, 31.5, and 32.1 bar were observed for UG, DMC10, DMC20, and DMC30, respectively, at 25 Nm load and 2800 rpm.

The effect of adding DMC to gasoline on ROHR and its variation with the crank angle are shown in Figure 11. In general, the oxygenate blends of DMC/gasoline have a higher rate of higher heat release than gasoline. The maximum ROHR of 58 J/deg was observed for DMC 30, followed by 56, 54, and 52 J/deg for DMC 20, DMC 10, and UG, respectively. The heat release rates exhibited a trend similar to in-cylinder pressures. By increasing the DMC content in DMC/gasoline blends, the ROHR also increases. DMC has a higher latent evaporation heat than gasoline, making the air intake colder. The colder air contains more oxygen because of its higher density, allowing more oxygen into the combustion process [38, 39]. More oxygen supplied to combustion due to a higher density of air and oxygen content in the DMC will result in complete combustion and hence high heat release rates and in-cylinder pressures [40, 41].

4. Conclusions to prospects

This work presents DMC performance and emission characteristics at 3 different concentrations (DMC 10, DMC 20, and DMC 30) tested in the multi cylinder MPFI engine. The purpose of this study is to compare a commercial engine running on high oxygen percentage DMC gasoline to an MPFI engine that has not been modified. This type of oxygenate can replace the octane enhancer in the fuel market by doing this successful experimentation. The following results are obtained from this study:

- The BTE was found to increase with the increased blend percentage. BTE was 11.82%, 12.45%, 13.37%, and 14.98% for gasoline, DMC10, DMC20, and DMC30, respectively, at 1400 rpm.

- CO and HC emissions were reduced for all the blends compared to unleaded gasoline. Reduced HC percentages of 6.77%, 15.25%, and 16.94% are observed at 2800 rpm for DMC 10, DMC 20, and DMC 30 compared to unleaded gasoline.
- NOx increased with the DMC percentage in the blends. At lower speeds, the NOx emission was less compared to higher speeds.
- It is observed that with the addition of DMC, the peak pressure value increased. The peak pressures observed with gasoline, DMC 10, DMC 20, and DMC 30 are 30.7 bar, 31.1 bar, 31.5 bar and 32.1 bar respectively. The peak pressure for gasoline is 11^o ATDC and 9^o ATDC for DMC 30.
- Compared to gasoline, DMC (DMC 10, DMC 20, and DMC 30) blends produced higher heat release rates of 10.4%, 7.1%, 4.3% respectively. Higher heat release rates are observed with DMC 30.

The results show that DMC/gasoline fuel can be used in SI engine to improve BTE, combustion stability and reduce CO and HC emissions. But higher level of NO_X is produced by DMC/gasoline blends, this can be controlled by varying the ignition time. In the future, the possibility of combining a dual oxygenate with gasoline could be explored as a potential strategy to further mitigate NOx emissions.

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Table captions

Table 1. Specifications of test engine.

Figure captions

Table 1. Specifications of test engine.

Technical Characteristics	Unit	Specifications
Engine Manufacturer, model	-	Maruti, Zen
Engine type	-	4-cylinder, 16-valve, Water-cooling, SOC
Control type	-	Group Ignition, MPFI Sequential
Air Induction System type, Ignition type	-	Atmospheric, Electronic
Bore, Stroke	mm	72, 61
Displacement	L	0.93
Volumetric Compression Ratio	-	9.4: 1
Maximum power	kW	45 (@6000rpm)
Maximum torque	Nm	78.48 (@4500rpm)

Table 2. Properties of test fuel.

Property	Unit	Gasoline	DMC
Chemical formula	-	C_4-C_{12}	$C_3H_6O_3$
Origin	-	Pump gasoline	Oxidative carbonylation
Oxygen	% by wt.	-	53.3
Density	Kg/m^3	0.768	1.063
Latent heat of vaporization	KJ/kg	305	369
Octane number	-	92-98	101-116
Auto ignition temperature	^oC	~300	458
Boiling point temperature	^oC	38-204	90-91
Stoichiometric air-fuel ratio	Kg/kg	14.7	3.5
Calorific value	MJ/kg	44	15.78

Table 3. Properties of DMC/gasoline blends.

Fuel type	γ	ρ_f	h_f	ϕ_f	ON	RON*
Unit	~	(kg/m^3)	(MJ/kg)	(kg/kg)	~	~
UG	0.0	0.768	44.00	14.7	92	86.33
DMC10	0.1	0.797	40.23	13.2	93.6	93
DMC20	0.2	0.827	36.74	11.8	95.2	97.67
DMC30	0.3	0.856	33.49	10.5	96.8	101.33

Table 4: Measurement accuracy uncertainty details

S. No	**Parameters measured**	**Range**	**Instrument Accuracy**	**Estimated Uncertainty**
Performance measuring instruments				
1.	Engine Speed (rpm)	0-1850 rpm	±25 rpm	+ 0.5%
2.	Crank angle	$0-360^o$	$\pm 0.1^o$	+ 0.5%
3.	Pressure	0-350 bar	+ 1 bar	+ 0.4%
4.	Temperature	$0-1500^oC$	$\pm 1^o$ C	+ 0.15%
5.	Time	0-60s	± 0.2 s	+ 0.25%
Properties measuring instruments				
1.	Density	$0.60-1.160 g/m^3$	$\pm 0.01 g/m^3$	0.12
2.	Octane analyzer	0-110 RON	±1	0.1
Emission measuring instrument				
1.	CO_2	0-20% vol	± 0.1%	+ 0.25%

2.	CO	0-10% vol	± 0.01%	+ 0.25%
3.	NOx	0-5000 ppm	± 1	+ 0.2%
4.	HC	0-10000 ppm	± 1	+ 0.2%
5.	O_2	0-50% vol	± 0.01%	+ 0.1%

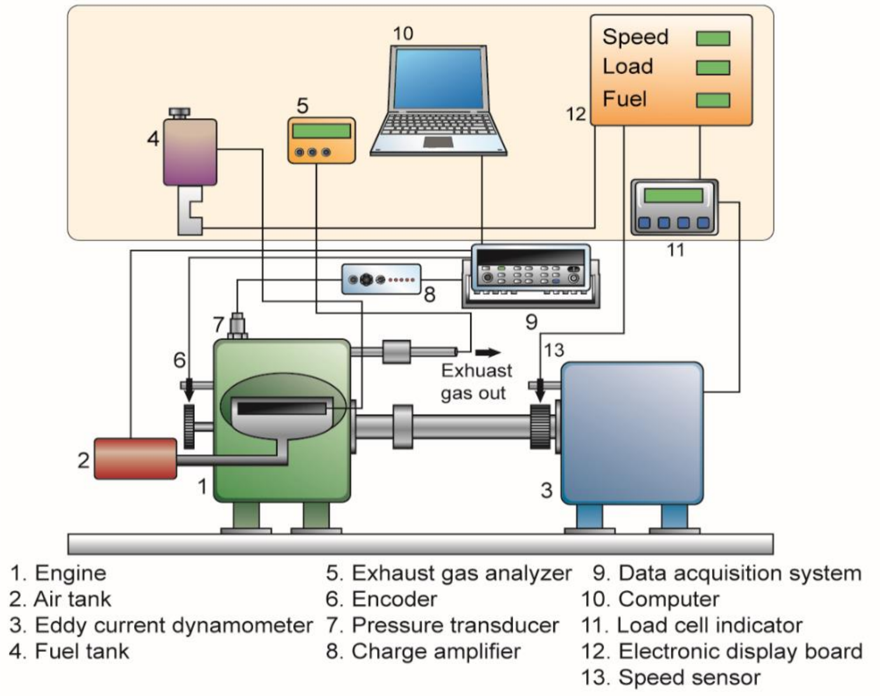

Figure 1. Experimental setup.

Figure 2. Photographic view of the engine with an experimental setup.

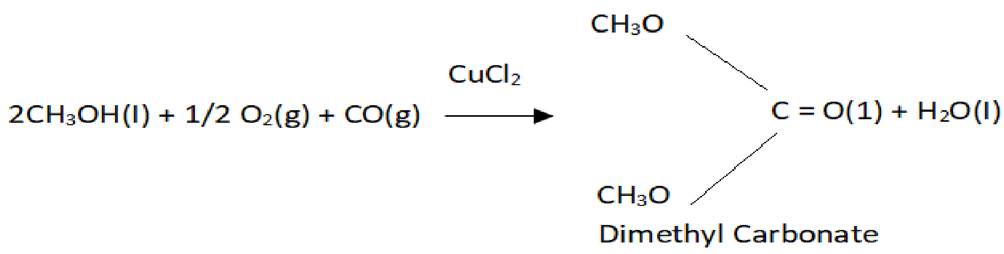

Figure 3. Synthesis of DMC.

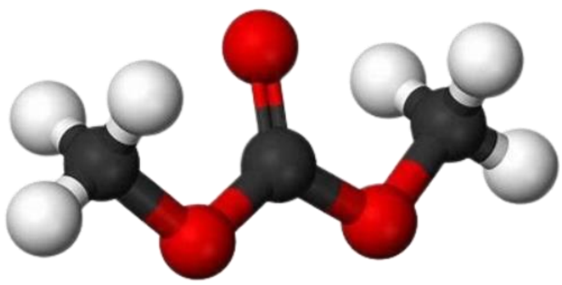

Figure 4. Molecular Structure of DMC.

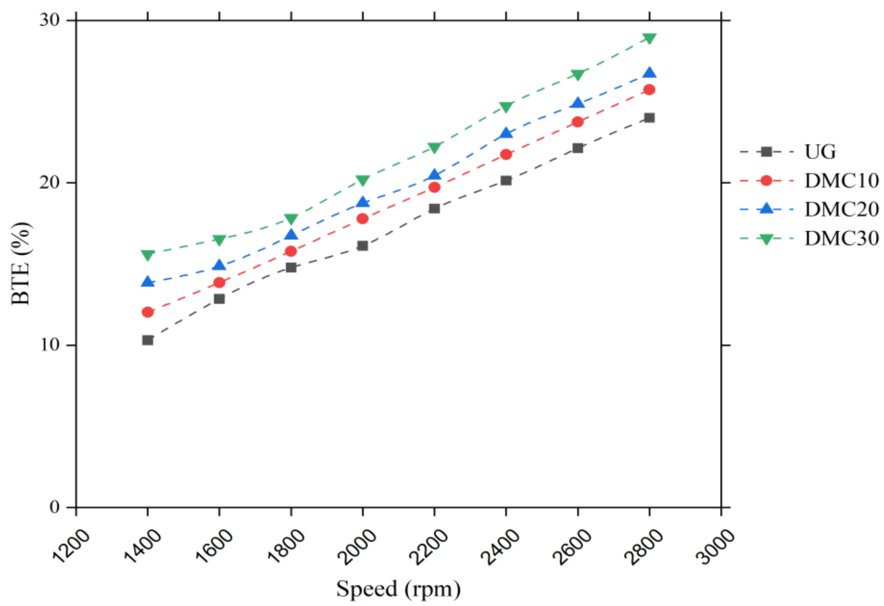

Figure 5. BTE for different engine speeds.

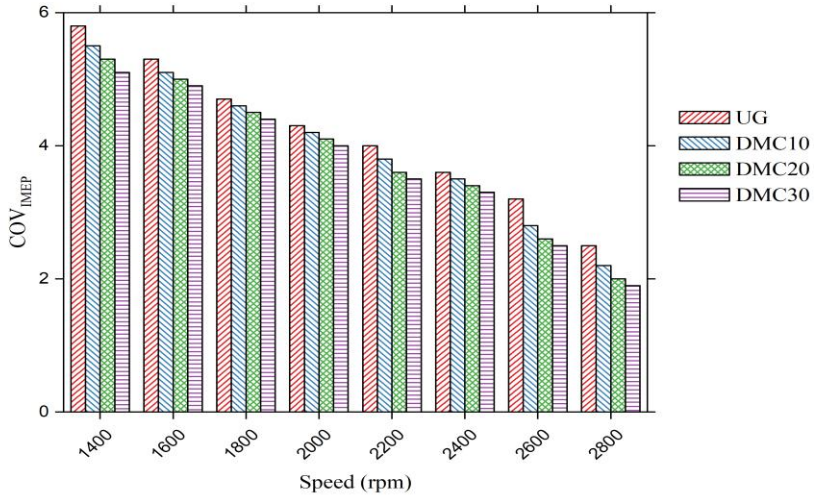

Figure 6. COV$_{IMEP}$ for different engine speeds.

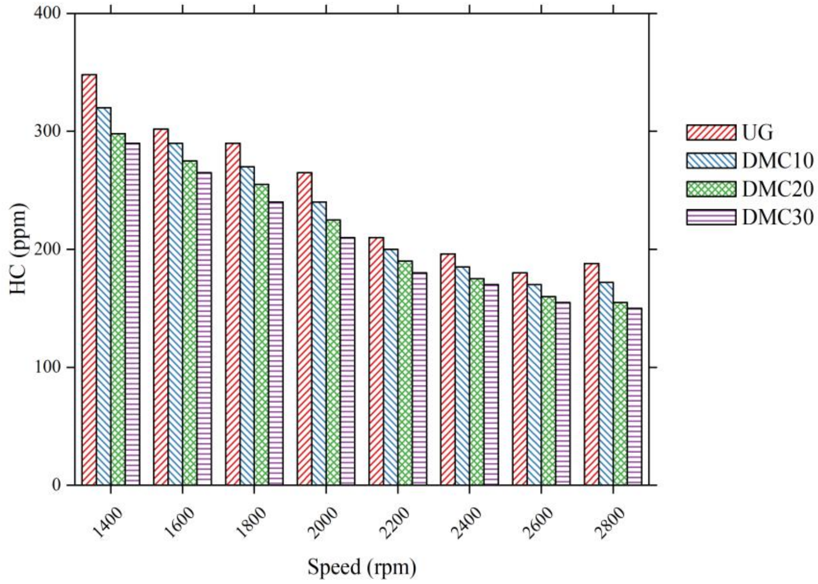

Figure 7. HC emission for different engine speeds.

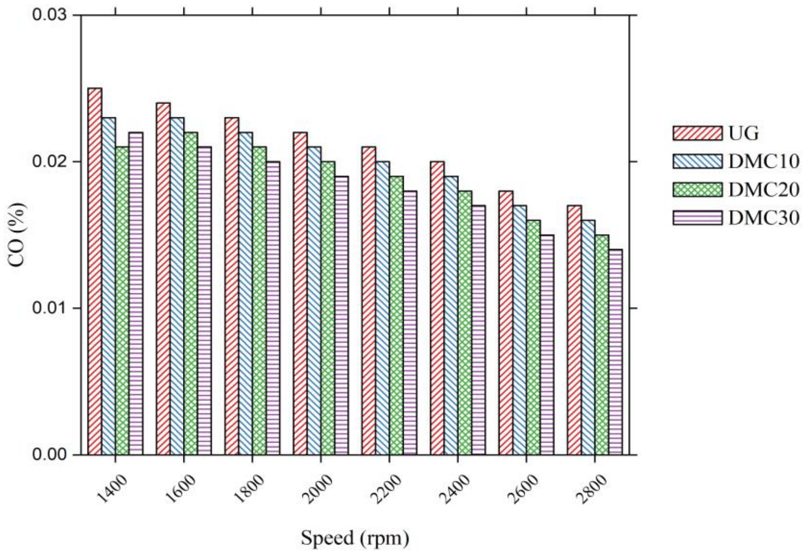

Figure 8. CO emission for different engine speeds.

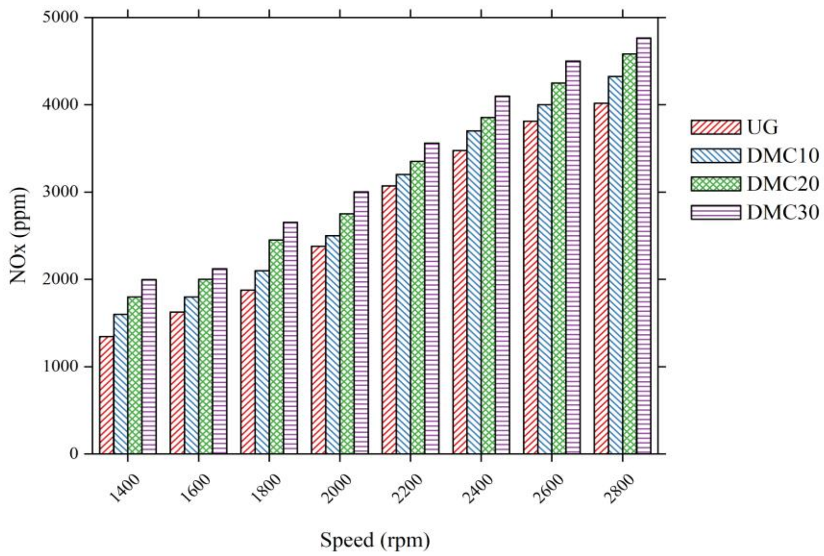

Figure 9. NOx emissions for different engine speeds.

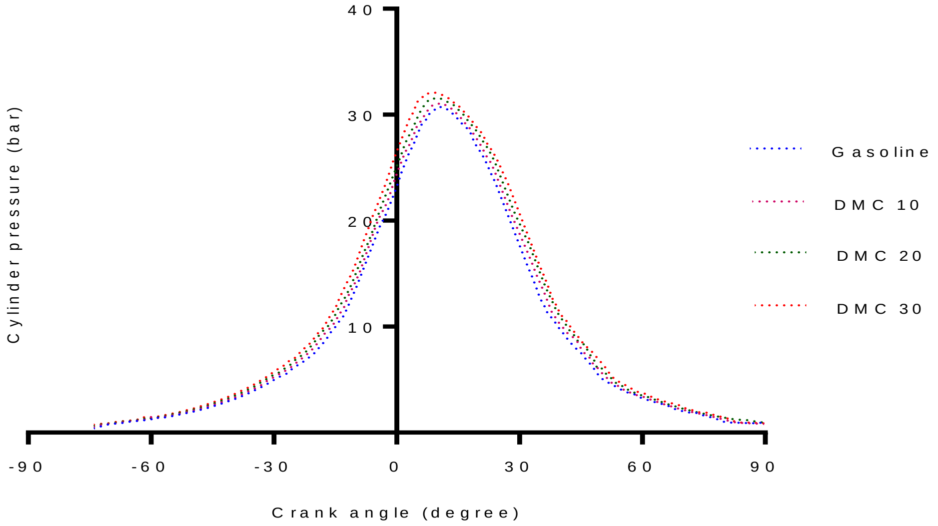

Figure 10. In-cylinder Pressure vs. crank angle.

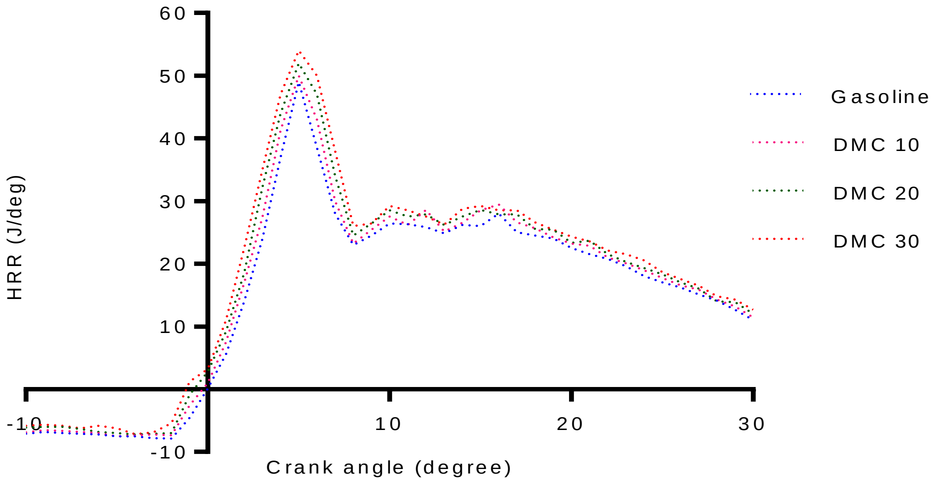

Figure 11. Heat Release Rate vs. crank angle.

Biographies

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